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FLOW VISUALIZATION OF CFD USING GRAPHICS WORKSTATIONS

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Abstract

High performance graphics workstations are used to visualize the fluid flow dynamics obtained from supercomputer solutions of computational fluid dynamic programs. The visualizations can be done independently on the workstation or while the workstation is connected to the supercomputer in a distributed computing mode. In the distributed mode, the supercomputer interactively performs the computationally intensive graphics rendering tasks while the workstation performs the viewing tasks. A major advantage of the workstations is that the viewers can interactively change their viewing position while watching the dynamics of the flow fields. An overview of the computer hardware and software required to create these displays is presented. For complex scenes the workstation cannot create the displays fast enough for good motion analysis. For these cases, the animation sequences are recorded on video tape or 16mm film a frame at a time and played back at the desired speed. The additional software and hardware required to create these video tapes or 16mm movies are also described. Photographs illustrating current visualization techniques are discussed. Examples of the use of the workstations for flow visualization through animation are available on video tape.

I. Introduction

Scientists are now able to obtain solutions to very complex fluid flow fields using new supercomputers and new numerical algorithms. However, these solutions alone are no longer adequate to gain an understanding of the flow field mechanisms -- displays clearly presenting key features of the flow phenomena are now also required. Creating good visualizations of key features is becoming a major task in itself. This paper describes the application of high performance interactive computer graphics at the NASA Ames Research Center to create the dynamic displays required for the analysis of complex 3D fluid flow fields.

The requirements for graphics in Computational Fluid Dynamics (CFD) are discussed in Sect. II. These requirements are based in part on experience with visualization techniques in experimental fluid dynamics. The requisite hardware and the software environment at Ames are described in Sect. III and IV. While graphics workstations are a central ingredient in the graphics approach at Ames, they are in fact only a part of a system of supercomputers, mass storage and communication networks needed to support large scale scientific calculations. A review of current visualization techniques used in CFD at Ames is given in Sect. V. An attempt is made to indicate how these techniques assist the user in the overall CFD process. The principal visualization techniques are discussed in Sect. VI, and conclsions are presented in the final section.

II. Requirements for CFD Graphics

The visualization of fluid phenomena is a very old technique in experimental fluid dynamics. It is very natural for the CFD scientist to want to use computer graphics to provide numerical flow visualization for his numerically simulated flows. Until a few years ago CFD graphics generally referred to static 2D pictures that were produced at the end of long batch jobs. Graphics was rarely done interactively. Animated movies were made, but the process was very slow and awkward; movies were not a routine way of studying CFD results. Some of the requirements for CFD flow visualization and current techniques are discussed by Buning and Steger[1] and are reviewed below.

The visualization techniques used to date consist of creating scenes to represent the flow field (usually 3D dynamic scenes) and providing the tools to let the viewer move his viewpoint thoughout the flow field, zooming in on features of interest and shifting about to get different perspectives or to get a better view of the three dimensionality. The tools to interactively change the viewpoint were found to be very important for effective and efficient understanding of the flow fields. Visualizing all three dimensions simultaneously with a display on a 2D screen is not satisfactory unless some strong cues to enhance the three dimensionality are used. Rotating the flow field (or equivalently rotating the viewer about the flow field) was found to be one of the best cues for enhancing the three dimensionality. Other cues used are solid body representation with hidden surfaces removed and shading from the various lighting models.

Some of the scenes currently used are simulation of particles released in the flow field, contour plots, shown either on planes slicing through the scene or on the surface of an object of interest, and scenes with multiple surfaces using transparent surfaces or color coded carpet plots. These scenes are illustrated on the video tape or 16mm film and with still pictures in the paper.

The views of the flow fields portrayed by the computer graphics displays must clearly present three dimensions because the dynamics of many flows of interest is highly three dimensional. The displays must be dynamic in order to understand the dynamic features of the flow fields. Although the motion need not be real time, the motions must be rapid enough to gain a proper understanding of the dynamical features of the flow. The flow fields typically have a large range of scales; therefore, the scientist must be able to zoom into a region of small scale features and zoom back out to view the overall flow field. Furthermore, the displays should have high spatial and color resolution to contain adequate detail. The displays must be capable of simultaneously showing solid objects, such as an aircraft with hidden surfaces removed, and points or lines, such as lines representing the paths of tracer particles inserted into the flow field. The display of transparent surfaces is required for viewing such features as shock waves with the object creating the shock wave visible behind the wave. The viewer's 3D viewing position must be changeable in real time, either while the flow dynamics is frozen or while the fluid is still in motion, in order to maintain the best view or to get different perspectives.

III. Requisite Hardware

In this section the hardware necessary to visualize CFD solutions is discussed. While the graphics workstation is a central ingredient, computer networks, mass storage, and various color hardcopy devices are also necessary. Most of the workstations at Ames are part of the Numerical Aerodynamic Simulation (NAS) Program, described in greater detail in ref. 2. In this paper the NAS facility will be used as a model for a graphics workstation environment.

Through competitive procurement the NAS Program selected the Silcon Graphics, Inc. (SGI) workstation known as the IRIS (integrated raster imaging system). A block diagram of the IRIS is shown in Fig. 1. The Motorola 68020 chip and the Weitek chip set give the workstation a floating point capability greater than that of a VAX 780 with floating point assist. This capability permits 2D calculations to be performed on the IRIS itself. In addition flow field solutions can be rendered --- converted to graphical data --- on the workstation.

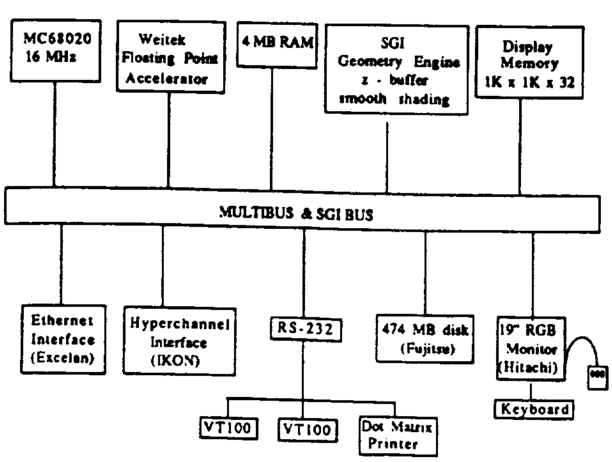

Figure 1. Block diagram of IRIS graphics workstation

The unique feature of the IRIS is the Geometry Engine. It consists of 12 VLSI chips which perform the floating point calculations needed to transform, project, and clip geometrical data for display on a CRT. The IRIS performs transformations at a speed which requires Geometry Engine performance in excess of 10 MFLOPS. 3D coordinates can be transformed at a rate of 80,000 coordinates per second. Points and lines can be generated at 3 million pixels per second (40,000 inches per second). Solid polygons can be filled at 44 million pixels per second (6,000 square inches per second). Therefore, displays with thousands of lines or points and with a simple solid object can be generated at a rate of more than 10 displays (frames) per second -- a rate that provides satisfactory motion for understanding dynamics.

Some rendering of the graphics, including z-buffering (hidden surface removal) and Gouraud shading, is also done in hardware. The 32 bit planes of 1 K by 1K resolution display memory can be configured in several ways. For animation two buffers of 12 planes each are used in a "double buffer" mode, where one buffer is displayed while the other is being drawn. Full RGB color, more than 16 million simultaneous colors, is obtained by using a single 24 bit plane buffer. Hidden surface removal is provided by using 16 planes for a z-buffer and 16 planes for color. Many seconds are required to create displays of typical aerodynamic vehicles if the z-buffer and Gouraud shading are used. Therefore, these displays must be recorded on video tape or 16mm film to view the dynamics satisfactorally.

The IRIS is configured to support two kinds of local area networks, HYPERchannel and Ethernet. The Ethernet interface is standard on workstations these days. The HYPERchannel interface was added to permit direct connection to supercomputers. Figure 2 is a block diagram of the computers and communication network in the NAS Program. All the systems except the Cray 2 are connected via Ethernet. This network has a physical bandwidth of 10 Mbit/s; the actual throughput to an IRIS disk from the Cray 2 is about 250 Kbit/s. In order that all the workstations have direct access to the supercomputer, the NAS Program also has a HYPERchannel network from Network Systems Corp. which provides a 50 Mbit/s physical bandwidth. Throughput to IRIS disk from the Cray 2 is about 2 Mbit/s and to IRIS memory, about 4 Mbit/s.

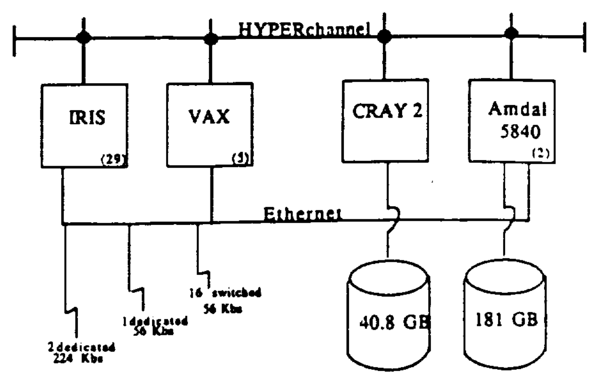

Figure 2. The NAS computers and networks

The third network of the NAS Program is a long-haul or wide area network known as NASnet. It provides Ethernet access for over 60% of NAS users. This network connects the local NAS Ethernet to remote site Ethernets via Vitalink TransLAN communication bridges. The necessary terrestrial communication links are provided by NASA's newly implemented Program Support Communication Network (PSCN). This long-haul network has been in a prototype mode for over two years. In particular, IRIS workstations located at Langley (LaRC) and Lewis (LeRC) Research Centers have Ethernet access to the NAS network.

The final ingredient for a successful graphics environment is the ability to make quality color hardcopy of what appears on the IRIS screen. There are two facilities available at Ames, one for making static pictures and one for making animations. The hardware for recording the displays on color prints is shown in Fig. 3. The Dunn Camera works directly

Configuration for Color Film Recording

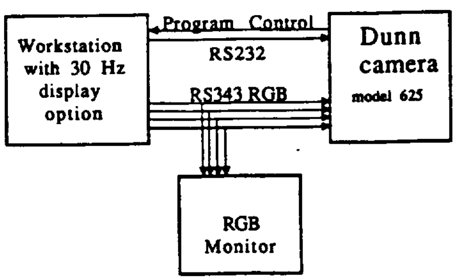

Figure 3. Hardware configuration for color print production

from the RGB Sync of the IRIS. Color polaroid prints can be made in minutes in both 4 x 5 and 8 1/2 x 11 inch formats with Dunn model 635. Color transparencies can also be made. The Dunn Camera model 632 with a similar interface to the IRIS is used to make 16mm movies.

The IRIS can provide adequate dynamic 3D viewing for images that are not too complex. For more complex images, the time to create the displays on the IRIS becomes so long that the motion is too slow to portray the flow dynamics effectively. For these cases, the displays are recorded a frame at a time on video tape or 16mm film and then played back at the desired speed.

The hardware used to record displays on video tape is shown in Fig. 4. The Abekas digital disk system is used to digitally record analog NTSC video. The system allows for storage of up to 100 seconds of this video on four winchester disk drives. These disks store 1.3 gigabytes of data. The system also includes a digital special effects loop that allows for digital information contained on the disk to be mixed with other input signals, or with other data already on the disk while special effects such as windowing, dissolves, etc. are added. The system records in real-time and suffers none of the generation losses inherent in analog video recording systems.

The RS170 signal leaves the IRIS workstation and runs to a distribution amplifier to bring the RGB signals up to acceptable levels for encoding. An RS170 monitor allows this signal to be previewed. The sync generator provides a timing signal to synchronize various video signals in the system. The IRIS usually sends the sync pulse out, but with the CG1 board installed (Silicon Graphics option) the system can be genlocked. This allows for broadcast quality results.

The encoder sends analog NTSC to the special effects portion of the system which then passes the signal on to the digital disk. Mastering is done to 1" video tape and time base correction is done to assure broadcast quality results when 3/4" copies are required.

The system is run by software that resides on the IRIS and sends control information to the Abekas hardware via RS232 protocol. The Abekas can then send information back to the IRIS in the same manner. The control panels are used when the system is operated manually, during playback of pre-recorded segments, and during the mastering process.

IV. The Software Environment

All the computers in the NAS Program use UNIX for their operating system. The choice of a common operating system has several advantages. The CFD user has only one set of commands to use as he moves from one computer to another. It is easy to bring new computers into the environment since system monitoring and applications software can be expected to run with few changes. Writing distributed applications --- those which span two or more computers --- is easier.

It is networking software which ties together the computers in the NAS System. Both the Ethernet and HYPERchannel networks are driven with the DOD transmission control protocol/ internet protocols (tcp/ip). This protocol is supported by many vendors and under operating systems other than UNIX, such as DEC's VAX/VMS. The CFD user interfaces to tcp/ip

VIDEO RECORDING with ABEKAS SYSTEM

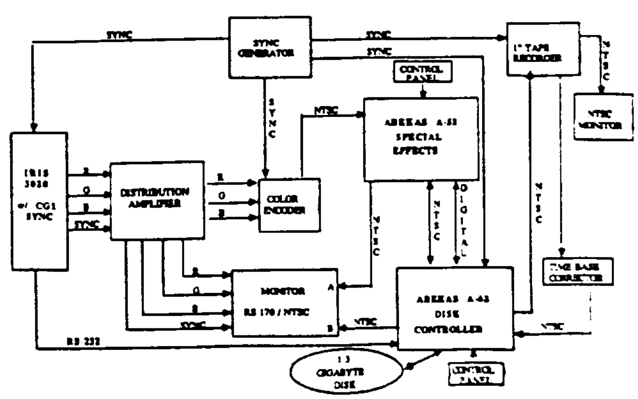

Figure 4. Hardware configuration for video tape recording

with a series of commands developed at the University of California at Berkeley. These commands give the user the ability to remotely log into other machines on the network or to do remote copies of files across the network. In addition the more sophisticated user can use system calls to have a process on his workstation execute tasks on another computer on the network. A recent extension of this capability is Sun Microsystems' network file system (nfs). This system lets a workstation user attach a file system on another machine to his file system. For example, a user can issue an edit command for a file that actually resides on the Cray 2. nfs will copy the file from the other computer to workstation memory transparently to the user. When the user saves the file, nfs will return it to the Cray, again without explicit user intervention.

There are presently four major graphics applications programs at Ames for creating and interactively viewing scenes of flow field solution:

PLOT3D

This is an "applications-level" program[3] in that it deals specifically with CFD grids and data. It has been implemented on IRIS, VAX, and Cray computers. PLOT3D is based on the premise that the interactive examination of computed results is one of the primary tasks which occupies the researcher. It takes as input the original CFD grid and solution; plots are produced directly on the graphics terminal. The program allows the selection of different subsets of the original data, the plotting of a variety of functions based on the solution variables (such as Mach number, pressure, vorticity, etc.), changing the number and color of contours, and, on the IRIS workstation, the real-time rotation and translation of the picture on the screen. Some flow visualization techniques are also built into PLOT3D: a rudimentary scheme to find and display shock waves, and particle tracing to simulate smoke in a wind tunnel or oil smears on the surface of a wind tunnel model. PLOT3D does **not** show motion of the particle traces (but does save (x, y, z) and time information for further processing), nor will it display a series of frames in a "movie mode". These can be done using GAS, as described below.

While the expected CFD solution file and computed functions are based on the Euler or Navier-Stokes equations, the code can, with some effort, be modified for other equation sets. This assumes that, independent of the equations, most quantities to be plotted are either scalar or vector fields. The interface to the graphics library (either ISSCO's DISSPLA or the IRIS library) can be modified as well to accomodate different graphics calls.

GAS

This is a program[4] to interactively set up and view flow field scenes on the IRIS workstation. The scenes, which can also contain dynamic [illegible]s, are created with software such as PLOT3D or ARCGraph (discussed below). Input to GAS is in the form of device independent .GRA files, generated using the ARCGraph GRAFIX library. GAS is also used to interactively record on videotape or film an animation sequence displayed on the IRIS. An animation sequence implies moving the image around on the screen (3D translation, rotation, zooming, etc.) and/or looping through a series of frames, representing a time-varying process or a sequence of slices through a 3D grid. When a researcher wants to see a movie-mode playback of an animation sequence, record a movie to make a presentation, or simply examine single frames or objects, he uses GAS. Output of GAS is pictures or movie sequences on the IRIS screen, videotape, or 16mm movie.

Due to the flexibility of dealing with purely graphical information, multiple plots can be overlaid, allowing the comparison or correlation of different functions or data sets. An interactive titling and text overlay capability, including several fonts, is available in GAS as well. These types of features are very valuable for both day-to-day research and final copy/presentation preparation.

ARCGraph

This is a collection[5] of graphics libraries and utilites, installed on many computers at Ames. Of particular interest is the GRAFIX library, which supplies the graphics calls to generate device independent ".GRA" files, which can serve as input to GAS. A version of PLOT3D is available which generates .GRA files and can thus be used to make sequences of frames to be "animated" by GAS.

RIP

The most recent and perhaps most interesting graphics application at Ames is RIP --- remote interactive particle tracer. RIP binds the Cray 2 and IRIS into a graphics coprocessing team. It requires a synthesis of UNIX networking software, the graphics interface of GAS, and particle tracing code on the Cray. The UNIX and communications system issues associated with RIP are discussed by Choi and Levit[6]. Two specific distributed applications, RIP and PLOT3D, are described by Rogers *et al.*[7].

Figure 5 illustrates the RIP application. It involves two processes, one on the IRIS and one on the Cray 2. These processes communicate over Ethernet or HYPERchannel using tcp/ip protocols. The process on the IRIS uses a graphics data base for the geometry of the object under study, such as the space shuttle or a new fighter design. The IRIS can rotate and translate this object in near real time, completely independent of the Cray. The IRIS also provides the principal interface

rip: A paradigm for Visualization in CFD

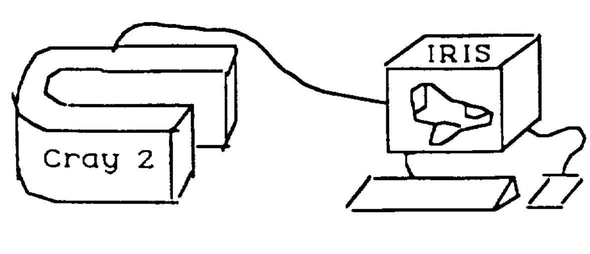

Figure 5. RIP: an example of distributed scientific graphics

to the user in this application. The process on the Cray 2 uses the solution data base for the object under strudy. This data base is the result of solving partial differential equations which describe the fluid flow. It is typically 50MByte in size and required 1 to 20 hours of Cray time to calculate. Although RIP was designed to be a graphics post processing tool, some CFD users have incorporated RIP concepts within the flow solvers so that they can interactively monitor the solution process with graphics.

The CFD scientist uses RIP by indicating with the mouse a point on or near the object where he would like to release a test particle. When he clicks a mouse button, the location of the point is sent to the Cray. It in turn interpolates through the flow field solution data base to figure out where the particle will flow. This technique is referred to as particle path tracing. The Cray 2 is very useful for finding particle paths. The search procedure is CPU intensive, and the data base can be very large. While particle tracing can be done on the IRIS, the process can hardly be called interactive. In roughly 1/10 of a second, the Cray returns to the IRIS a series of perhaps 400 short vectors which define the particle trajectory.

In a matter of minutes the CFD user can define and build up a visualization of the flow field over the object of interest. At any point he can rotate the object and the traces to study the flow from different orientations. In this way he can correlate what happens in one area of flow with another. RIP provides him an interactive tool with which to visualize, to explore the results of his flow field calculation. Since RIP sends display list information, not image or pixel data, to the IRIS, all viewing and manipulation of geometry and traces can be done independently of the supercomputer.

V. Review of Current Visualization Techniques

In this Section a set of plates is presented to illustrate current visualization techniques used at Ames. These pictures are taken from the various stages of the CFD process to illustrate how graphics assists the CFD user in his research.

The first step of any CFD calculation is "body definition". This is the task of numerically defining the surface or body over which a flow field is to be calculated. The act of body definition determines the greater part of the boundary conditions for solving the partial differential equations used to calcuate the flow. The accuracy of the flow field calculation depends in part on the accuracy of the body definition. With new supercomputers CFD researchers will increasingly use the Navier-Stokes equations to compute flow over ever more complicated 3D geometries. Graphics will play an ever more critical role in verifying the definition of such geometries. Plate 1 from Cozzolongo[8] illustrates this in several ways. The large holes in the wings of the pictured aircraft are so obvious that they could probably be found by scanning a list of numbers. The thin blue crack just above the wing root signals a small but critical error in defining wing-body coordinates. The plate shows many of the shading and highlighting effects that are essential for verifying a smooth body definition.

The second step of the CFD process is the discretization of space around the body --- the making of a grid. A cut-away view of a grid about an F16-like body from Sorenson[9] is shown in Plate 2. Presently such grids are still developed non-interactively. Graphics is used to verify detailed features of the grid such as local orthogonality of grid lines to the body surface. As faster methods to compute grids are developed, graphics will begin to play a role in creating grids interactively. Software which would let a user pick and stretch grid lines to form a better grid could greatly accelerate the process of making a grid.

The next step in the CFD process where graphics plays an important role is the analysis stage. The user has obtained flow field solutions on his supercomputer. He wants to verify that expected physics is present in his calculation. More importantly, he wants to learn what new physics his simulation has to tell him. Plates 3 to 7 illustrate several techniques for graphically assessing flow field results.

Plate 3 from Reznick and Flores[10] shows particle traces over an F16-like geometry. This image was first constructed using a program such as RIP. The interactive environment that RIP offers allows the user to build up an intuitive feeling for the flow field as he defines such a picture. Each of the paritcle traces consists of hundreds of short vectors. Using a program like GAS, the user can "play back" these short vectors to get an animated feeling for air flow over the object. The particle trace technique has an unexpected usefulness. The amount of data associated with a single trace is not very large. This means that remote users of supercomputers can do graphics with programs like RIP over long-haul lines running at 56 Kbit/s. As current solution files are 50 MByte or so in size, they would take hours to send to the remote user at these speeds.

Contour slices[10] in 3D are shown in Plate 4. The use of contour plots in two dimensions is a well known technique for isolating phenomena such as shocks. Its extension to 3D in the manner shown is natural. Color is used effectively here to define contour levels. In general visualization techniques for picking out new features in fluid flow in three dimensions are sorely lacking.[1]

CFD users are still experimenting with the use of color in flow field visualization. The principal use at the present time is to associate color changes with varying contour levels. This is illustrated in Plate 5 from Rizk *et al.*[11]. It shows a surface pressure map on a generic wing-body. The color spectrum is associated with pressure variation in this instance.

The techniques of particle traces and transparency are illustrated in Plate 6. Shown is the hot gas manifold of the space shuttle main engine as simulated by Yang *et al.*[12]. The short line segments indicate the sense of the fluid flow frozen in time. In the animated video one can follow the many traces as they move through the manifold. The manifold itself is drawn with a special polygon fill pattern which provides the illusion of transparency. Future graphics workstations will devote additional bit planes to transparency effects.

The final plate is a comparison by Hibbard *et al.* [13] of a calculated result with an experimental measurement. A photograph of flow over a simple airfoil[14] was digitized. The digitized data and a contour plot of the calculated result[15] were then shown simultaneously on the IRIS screen. Calculated and experimental data were scaled to obtain the best visual agreement. CFD users and graphics specialists at Ames are just beginning to explore such techniques.

VI. Discussion

The use of the techniques discribed above for visualizing flow fields --- (1) dynamic, interactive viewing on the workstation, (2) recording and playback on video tape, and (3) recording and playback on 16mm film --- have greatly improved the ability of the scientists at NASA Ames to conduct fluid dynamics research. There are no other techniques known to provide the scientist with the visualizations required to understand the complex simulations that can be performed on supercomputers.

Of the three techniques, the dynamic, interactive viewing on the workstation is by far the most effective and efficient. The key disadvantages of recording and subsequent playback are the loss of interactivity with the displays, the long time to do the recording, and, for video recording, the loss of spatial and color resolution. These disadvantages and some partial solutions to overcome them are discussed here.

With direct viewing on the workstation, the capability to interactively manipulate the viewing position and the animation sequence was found to be very effective in providing a quicker and more complete understanding of the flow field solutions. This capability is lost if the displays are so complex that they must be recorded for playback. A solution for this problem is to increase the performance of the workstation. The limitation for dynamic viewing directly with current workstations is the speed for creating solid object representations. For some simple shapes, a fast software algorithm can be written for hidden surface removal. However, the time required to execute software algorithms increases very rapidly with complexity and eventually surpasses the time required for the z buffer technique that is implemented with hardware. Typical scenes of aircraft now take many seconds to create using the z buffer; so at least two orders of magnitude increase in speed is required to perform dynamic viewing at a rate of 10 frames per second directly on the workstation. During the next year only one order of magnitude in speed of execution of z buffer hidden surface removal is expected. It will probably be several years before a scene with a complex aircraft shape will be viewable with satisfactory dynamics directly on a workstation.

Recording on video tape causes a loss in picture quality --- a loss in picture resolution and a shifting in colors. The intial spatial resolution must be cut nearly in half to 512 x 512 for the conversion to RS170A RGB format. The further encoding to a single composite video signal, NTSC, causes another substantial reduction in quality. There is no loss in quality during the editing process since pictures are stored digitally on the Abekas. Some quality is lost during recording to tape, but the use of 1" tape format minimizes this. Copies made from the 1" master are generally in 3/4 or 1/2 inch format; their quality will be reduced accordingly.

Recording on film requires a long time primarily because film processing is done off site. This processing time could be reduced from days to hours if a film processor were placed on site.

VII. Conclusions

The high resolution, high performance 3D graphics workstation combined with specially developed display and animation software has provided the scientists with a good tool for analyzing flow field solutions obtained from simulations on supercomputers. The visualization techniques described in this paper are expected to be just the first of many techniques that will evolve for using interactive computer graphics for the analysis of flow fields.

For very complex displays that cannot be created rapidly enough to yield satisfactory dynamics on the workstation alone, a video tape or 16mm film recorder and the controlling animation software are needed in addition to the workstation.

The limiting factor for good motion viewing directly on a workstation is the speed for solid body representation. The time required on current workstations to create a scene of the flow about a complex object such as an aircraft is two orders of magnitude too long. One order of magnitude increase in speed is expected this year, but it will probably take several years to reach the required speed on reasonable cost workstations.

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